IMPACTS OF LOW ALTITUDE ON STS-110 RENDEZVOUS

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ABSTRACT

The space shuttle Atlantis was launched on April 8, 2002 to the International Space Station (ISS). The primary payload carried aboard Space Transportation System mission STS-110 was the Integrated Truss Segment ITS-S0, a 13-meter (43 ft) long structure that forms the centerpiece of the station truss structure. Liftoff occurred 11 seconds from the end of the launch window, resulting in a large phase angle of 407 deg between the orbiter and the ISS. This required the orbiter to remain at a low altitude of 230 x 157 km (124 x 85 nmi) for several days until start of terminal rendezvous on flight day 3. This low altitude provided a shorter orbital period for the shuttle--over time nulling the phase difference with the ISS, which was in a 393 x 380 km (212 x 205 nmi) orbit. The altitude differential between the two vehicles also resulted in STS-110 having the highest closing rate at start of terminal rendezvous in the history of the shuttle program, 1800 km/revolution (970 nmi/rev). The pre-rendezvous phasing portion of this mission provided an opportunity to calibrate drag models with real-world data in the seldom-flown low-altitude regime. It was found that atmosphere models in both the Mission Control Center software ('70 Jacchia-Lineberry) and Orbiter software (Babb-Mueller) significantly over-modeled drag at low orbital altitudes. Post-flight analysis of several different atmosphere models revealed that the U.S. Committee On Extension to the Standard Atmosphere (COESA) model would have provided the best match with flight data. It was also found that the standard pre-rendezvous waste/supply water dump attitude-hold at low altitude resulted in large semi-major axis growth due to uncoupled reaction control system jet firings. Finally, it was confirmed that pre-mission rendezvous propellant cost estimates are accurate in this regime. This paper discusses these lessons in detail, and includes other general trajectory design considerations for large phase angle rendezvous missions.

PRE-LAUNCH TRAJECTORY DESIGN

A major consideration in the design of any mission to rendezvous with an orbiting spacecraft is the launch window. A shuttle launch window is the composite of both *planar* and *phase* windows. Planar window is defined as the time during which the target's orbital plane can be achieved by active steering during ascent. This is typically 10 minutes or less for a 51.6 deg inclination mission from the Kennedy Space Center (KSC), due to the limitation that only about 1,000 kg (2,200 lbs) of propellant be utilized for planar steering during powered flight (ref. 1). The optimal "in-plane" time occurs when the launch site rotates under the target's orbit plane, requiring no out-of-plane steering. While planar window is concerned with *lateral* trajectory control, phase window similarly limits the *longitudinal*, or in-track, trajectory. Phase angle is defined as the angle between the target position vector and the chaser position vector (projected into the target vehicle's plane), measured at some time. Standard shuttle ground-up rendezvous practice has the shuttle insert into a lower altitude relative to the target. This provides a shorter orbital period for the shuttle which allows it to phase, or catch up, with the slower-moving target above. The maximum and minimum altitude differential between the vehicles, together with constraints on time of rendezvous, define the phase

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angle limits for a particular mission. For rendezvous on flight day 3 with ISS in a 210 nmi circular orbit, the maximum phase angle is approximately 400 deg. To accomplish this, the required shuttle insertion orbit is as low as possible: 230 x 157 km (124 x 85 nmi). In this case, the shuttle would pass under, or lap the ISS at 360 deg phase angle some time after launch, and then continue closing the remaining 360 deg prior to docking. Minimum flight day 3 phase angle is around 36 deg, which is accomplished by inserting as high as possible in order to slow the phase rate, approximately 376 x 230 km (203 x 124 nmi). Typically the shuttle can rendezvous on flight day 3 or 4, with day 3 preferred since this achieves docking early in the mission, while providing adequate time for the crew to overcome Space Adaptation Syndrome. Flight day 3 rendezvous also provides an entire flight day 2 to perform equipment checkout and troubleshooting, plus it yields an in-plane launch window every day within allowable phase limits (ref. 2).

Table 1 shows the planned launch window for STS-110 as computed on L-1 day. Planar window times were computed using the Launch Window/Launch Targeting (LW/LT) program in the Mission Control Center (MCC). This program also computed phase angle at the time of the Orbital Maneuvering System insertion burn (OMS-2) at apogee one-half orbit after launch. Total ΔV cost of the rendezvous from OMS-2 to manual takeover at approximately 600 meters (2000 ft) range is shown in Table 1 for several points in the launch window. This also was computed on L-1 day using the Orbital Maneuver Processor (OMP), which is the primary rendezvous trajectory design program employed in the MCC. Table 1 shows that the close of the launch window was constrained by phase capability, rather than planar steering. Rather than accept loss of the last 1 min 40 sec of the launch window, or lose a docked day by downmoding to a flight day 4 rendezvous, an effort was made to allow for exceeding the maximum flight day 3 phase limit so the full planar window could be utilized. This will be described in more detail below.

Table 1. STS-110 Launch Window for April 8, 2002 Liftoff

LW Event	GMT	OMS-2 phase angle	Rndz ΔV	Notes
Planar Open	20:34:31	370 deg	146.6 mps (481 fps)	
In-plane	20:39:29	388	147.5 (484)	
Flight day 3 technical phase limit*	20:42:50	400	148.4 (487)	NC-1=2.0 mps (6.4 fps) NC-2=1.8 mps (6.0 fps)
Planar close	20:44:30	407	149.0 (489)	NC-1=0.1 mps (0.2 fps†) NC-2=6.0

*3σ confidence in no burns going retrograde
†Potential 3.7 mps (12 fps) propellant penalty due to possible retrograde burn(s)
All phase limits assume no ET photo +X translation

A fixed OMS-2 perigee of 157 km (85 nmi) was planned for the entire launch window. This was chosen to maximize phasing, and is the minimum height allowed by the shuttle program. Standard Main Engine Cutoff (MECO) velocity and flight path angle targets were utilized to place apogee at a fixed value of 226 km (122 nmi). Including impulsive effects of the Main Propulsion System (MPS) dump (performed 2 min after MECO), the initial orbit for the entire window was 230 x 157 km (124 x 85 nmi). The first phasing control maneuver, NC-1, was planned for two orbits after OMS-2. The purpose of this burn would be to target the orbiter for 74 km (40 nmi) behind the ISS on flight day 3 at the time of the NC-4 burn. The rendezvous plans included two small fixed ΔV maneuvers, NC-2 and NC-3. These maneuvers were biased posigrade in order to protect for perturbations that could cause an increase in semi-major axis (SMA). This posigrade bias was intended to minimize the likelihood that uphill SMA growth could force subsequent burns to go retrograde in order to re-establish the necessary phase rate. Retrograde burns are undesirable in shuttle rendezvous design due to the "double propellant penalty" of having to lower the orbit, then raise it back up after the phasing has been accomplished. A planar correction burn (NPC) was included in the plans to correct for any errors in the insertion orbit plane. Finally, all the plans featured similar day-of-rendezvous (DOR) profiles: a height adjust burn (NH), final phasing burn (NC-4), terminal phase initiate burn (Ti), and final midcourse correction (MC-4). Table 2 shows OMP rendezvous plan output for an in-plane launch. Note that all burns are posigrade. Figure 1 shows the planned day-of-rendezvous relative motion. Consult reference 3 for additional background on shuttle rendezvous trajectory operations.

Table 2. Rendezvous plan for in-plane launch (all units in English System)

MNVR TYPE	GMT IGN (d:h:m:s)	DVx (fps)	HA (nmi)	RANGE (nmi)	Y (ft)
COMMENT	MET IGN	DVy	HP	PHASE (deg)	Ydot (fps)
DVmag (fps)	Delta-T	DVz	Delta-H	Noon/Mid -	SR/SS -
1 HA	098:21:17:55.306	97.48	123.15	1777.7576	-234860.7
OMS-2	000:00:38:26.306	0.00	84.93	28.4582	-27.7
97.5	000:02:56:39.867	0.00	86.98	N-00:38:10	SR-00:09:33
2 NC	099:00:14:35.173	16.11	122.57	184.7131	-222742.8
NC-1	000:03:35:06.173	0.00	93.86	-2.5156	-25.7
16.1	000:13:16:23.642	0.00	87.50	N-00:46:11	SR-00:17:30
3 EXDV	099:13:30:58.816	8.00	121.47	6716.9905	-129477.5
NC-2	000:16:51:29.816	0.00	97.35	-137.1674	0.9
8.0	000:03:22:53.153	0.00	88.91	M-00:34:14	SS-00:16:28
4 NPC	099:16:53:51.968	0.00	121.12	7172.7704	24065.1
NPC	000:20:14:22.968	5.56	97.13	-170.3816	141.9
5.6	000:03:59:44.693	0.00	106.86	M-00:15:58	SR-00:33:44
5 EXDV	099:20:53:36.661	3.00	120.64	6958.7946	-101618.8
NC-3	001:00:14:07.661	0.00	98.65	149.1645	1.9
3.0	000:14:35:26.339	0.00	89.60	N-00:07:02	SS-00:35:23
6 NH	100:11:29:03.000	194.85	210.21	255.5105	-869.0
NH	001:14:49:34.000	0.00	116.31	3.7954	-2.2
194.8	000:00:44:23.000	0.00	90.52	M-00:08:22	SR-00:26:12
7 NC	100:12:13:26.000	147.36	210.80	40.0093	150.7
NC-4	001:15:33:57.000	0.00	198.80	0.6273	0.4
147.4	000:01:32:13.000	0.00	0.20	N-00:10:11	SS-00:38:25
8 SOI	100:13:45:39.000	8.77	211.54	8.1221	19.1
Ti	001:17:06:10.000	0.04	203.10	0.1273	0.1
8.8	000:01:16:54.000	-0.59	0.19	N-00:10:16	SS-00:38:29
9 SOR	100:15:02:33.000	2.51	211.56	0.3309	1.1
MC-4	001:18:23:04.000	0.02	204.54	0.0023	0.0
3.0	000:00:00:00.000	1.69	0.30	N-00:25:38	SS-00:53:42

Note: ΔV in Local Vertical/Local Horizontal (LVLH) coordinate system:
$+\Delta Vx$ posigrade, $+\Delta Vy$ opposite angular momentum vector, $+\Delta Vz$ radial down
Ignition times are impulsive

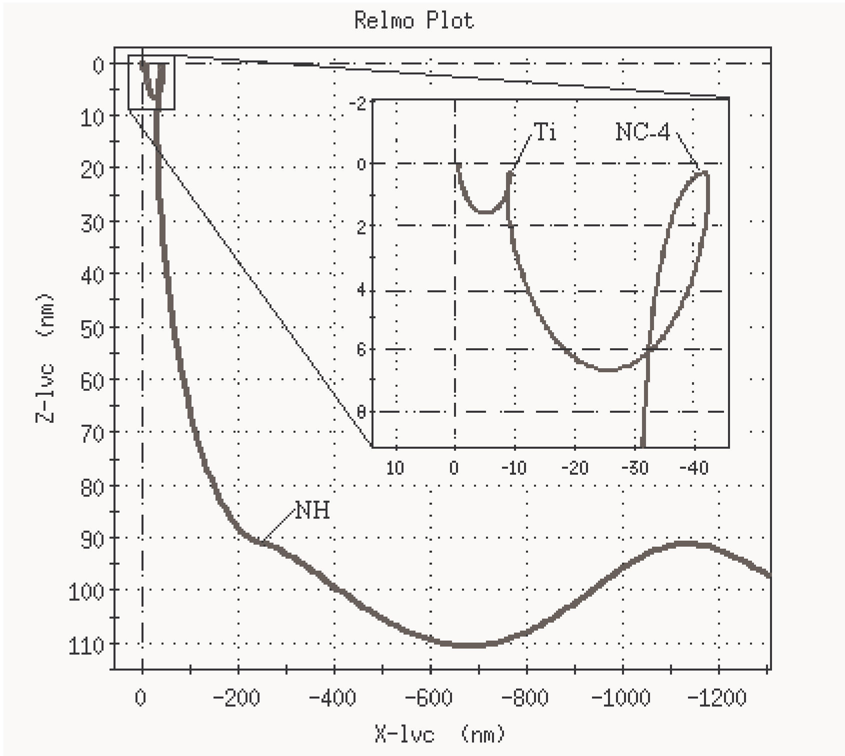

Figure 1 Planned Relative Motion

Note from Table 1 that at the flight day 3 technical phase limit of 400 deg, NC-1 ΔV is 2.0 mps (6.4 fps) posigrade. This, coupled with a fixed 1.8 mps (6.0 fps) NC-2, provided 3σ confidence that neither burn would go retrograde in the presence of various dispersions[‡]. These minimum "posigrade bias" burns were determined by Monte-Carlo analysis. Any phase angle greater than 400 deg would force a smaller (or even retrograde) NC-1 burn in order to achieve the desired phasing. The smaller the NC magnitude in a rendezvous plan, the greater the odds that these or subsequent burns could go retrograde in the presence of trajectory dispersions. For STS-110, the decision was made to allow propellant to be sacrificed from lower on-orbit priorities (ISS reboost, post-undock flyaround, etc) in order to protect past the flight day 3 phase limit, out to the end of the planar window. As will be seen next, this decision allowed launch to occur on April 8.

REAL-TIME TRAJECTORY OPERATIONS

The launch countdown was held at T-5 min to provide KSC personnel time to reboot ground front-end processors. This activity was completed just in time to allow the count to proceed. Actual launch GMT was 20:44:19, 11 seconds from the end of the planar window. This corresponded to a phase angle of 407 deg, 7 deg past the technical flight day 3 rendezvous phase limit. Ascent and OMS-2 were executed successfully, placing the shuttle in a 230 x 157 km (124 x 85 nmi) orbit as planned. The OMP was configured per Table 1, but for a maximum phase case NC-2 ΔV was fixed at 1.8 mps (6 fps). The first ground tracking pass on orbit 2 showed a 553 meter (1,814 ft) increase in SMA, which is equivalent to a MECO overspeed of about 0.3 mps (1 fps). This state vector update was input into the OMP, which generated a small retrograde NC-1 solution of approximately -0.3 mps (-1 fps). It was decided to cancel NC-1 and let NC-2 ΔV control phasing, even though its solution would decrease below 1.8 mps (6 fps). After the payload bay doors were opened, the shuttle maneuvered to a tail forward, payload bay-to-Earth

[‡] Primary uncertainties in orbit prediction: navigation errors during launch and insertion, SMA error introduced by uncoupled reaction control system firings, water dumps, attitude maneuvers, and atmospheric drag model uncertainty (ref. 4).

attitude. It remained in this orientation for over 24 hrs, providing the Ground Navigation team a long tracking arc during which an accurate drag solution could be obtained. This was the lowest average altitude ever maintained by the shuttle for an extended period, so it presented a unique opportunity to assess drag model accuracy in this regime.

Real-Time Drag Modeling

The principal method used to obtain a real-time drag solution was to first predict the shuttle's orbit using the MCC propagator, and then over time compare the actual orbit based on real-time tracking to that prediction. The propagator utilized for real-time shuttle operations computes variable-area drag with a '70 Jacchia-Lineberry atmosphere model (ref. 5). The Enke-Beta propagator features a 6th order Adam-Moulton-Bashforth numeric integrator using Goddard Earth Model-10 (GEM 10) 7 x 7 geopotential model. Perturbations due to solar and lunar gravity are also included.

Figure 2 illustrates the growing differences in SMA between the MCC prediction and the actual orbit, as determined with tracking data. A large and consistent SMA modeling error of approximately 110 m/rev (360 ft/rev) was detected soon after the maneuver to tail forward attitude. The posigrade direction of the SMA modeling error indicated lower than expected drag, or some vehicle propulsive force in a posigrade direction. Orbiter propellant usage at the time was reported by the MCC Propulsion Officer to be only "slightly higher" than normal usage, which discounted uncoupled thruster firings as a source of the perturbation. (Normal prop usage in this attitude is low, and SMA updates are typically under 8 m/rev (25 ft/rev)). Since the orbiter was in a stable configuration during this time period, with no attitude maneuvers, water dumps, or leaks, the most likely source of this perturbation was deduced to be drag-modeling error.

Ground Navigation personnel initially recommended a 1.2 N (0.26 lbs) posigrade vent force to correct ground drag modeling. A "vent" correction is routinely used in the MCC ephemeris generator to essentially calibrate the propagator to observed tracking. This applies a constant thrust force over the duration of a particular attitude-hold period in order to zero out the average SMA modeling error. At higher altitudes, a typical vent solution under 0.1 N (0.02 lbs) is obtained for this orientation. Therefore, the large update immediately raised concerns of the drag model's accuracy, and the effect this could have on the rendezvous plan. Figure 3 shows that the unmodeled SMA error growth continued after the NC-3 burn on orbit 17. A least squares fit of the data in Figures 2 and 3 show an SMA slope of 110 m/rev (360 ft/rev) and 106 m/rev (348 ft/rev) respectively.

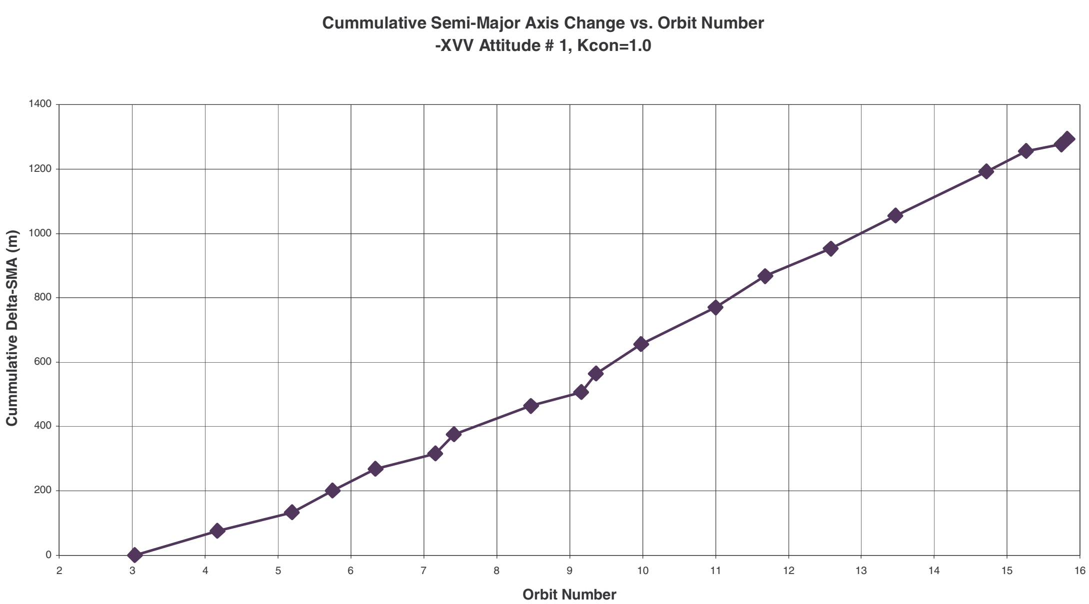

Figure 2 Unmodeled SMA Growth Prior to NC-3

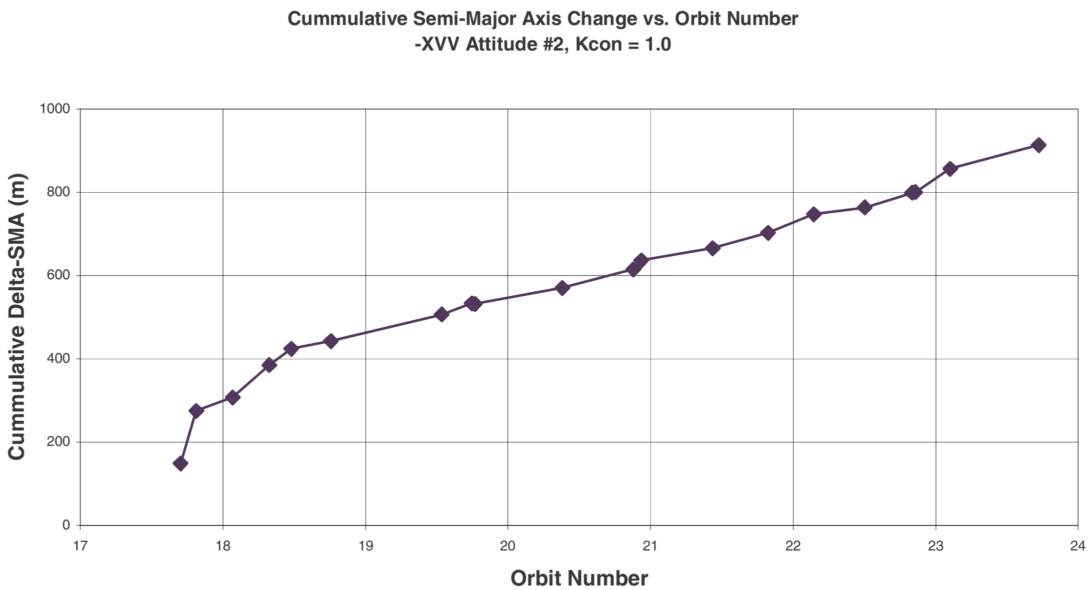

Figure 3   Unmodeled SMA Growth After NC-3

Analytic Drag Error Estimate

Change in SMA (Δa) due to drag over one revolution can be approximated as follows (ref. 6):

$$\Delta a_{rev} = -2\pi C_D \frac{A}{m} \rho a^2 \tag{1}$$

where: C_D = coefficient of drag
A = cross sectional area in the velocity vector direction
m = mass
ρ = density

If one assumes that the change in SMA is a function of drag only, then observed change in SMA is made up of the expected, or modeled, change in SMA plus some unexpected component:

$$\Delta a_{rev,observed} = \Delta a_{rev,modeled} + \Delta a_{rev,unmodeled} \tag{2}$$

where: $\Delta a_{rev,modeled} = -2\pi C_D \frac{A}{m} \rho a^2$

and

$$\Delta a_{rev,unmodeled} = -2\pi C_D \frac{A}{m} \Delta\rho a^2 \tag{3}$$

Equation (3) relates unmodeled change in SMA (Δa) to drag model density error (Δρ). STS-110 pre-rendezvous average unmodeled SMA growth was 107 m/rev (350 ft/rev), which equates to a density error of -1.9E-10 kg/m^3 (-3.6E-13 slugs/ft^3). The negative sign here means observed density was lower than expected. The following inputs were used in this calculation: C_D=2.0, A=120.7 m^2 (1,300 ft^2), mass=114,941 kg (253,400 lbm), a=6,568,440 m (21,550,000 ft). Average density for the STS-110 pre-rendezvous orbit as computed by Jacchia-Lineberry using an active solar cycle is 6.15E-10 kg/m3 (1.19E-12 slugs/ft^3). Comparing this to the density error computed above shows Jacchia-Lineberry over-predicted drag by 33%. This is consistent with the drag multiplier (KCON) of 0.7 that was computed in real-time by Ground Navigation personnel.

Drag Model Comparison

Different atmosphere models were examined post-mission to determine whether the drag level encountered on STS-110 could have been predicted more accurately. Figure 4 shows a comparison of the MCC's '70 Jacchia-Lineberry and other widely-used atmosphere models over a typical orbit during the low altitude portion of STS-110. The shape of the curves is due to the elliptical orbit, with perigee (max density) occurring at an MET of about 5.47 hrs. It can be seen that both the Jacchia (ref. 7) and speed-optimized Jacchia-Lineberry output highest densities. Next is the SPACECOM model, followed by Babb-Mueller (used in the shuttle flight software, ref. 8), and COESA, which is an extension to the 1962 U.S. Standard Atmosphere (ref. 9). Since COESA has 21% less density than Jacchia-Lineberry over a typical orbit, it would have provided the best match with the actual atmosphere during STS-110. More missions with long tracking arcs at low altitude will be required to validate this conclusion prior to following through with any ground model updates.

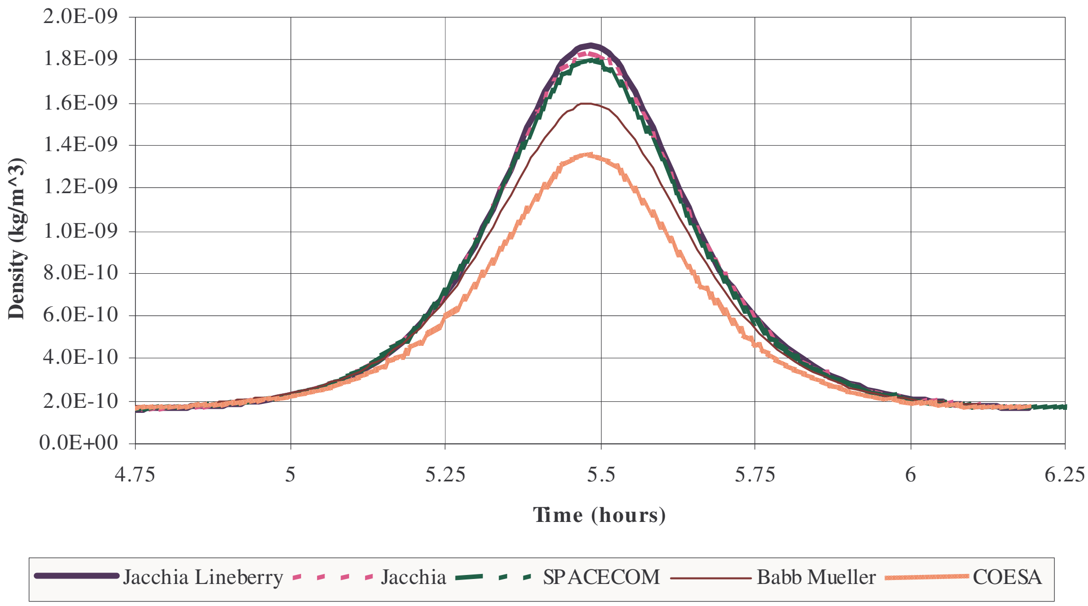

Figure 4 Atmospheric Model Density Comparison

Real-time Rendezvous Operations

By morning of flight day 2, the SMA trend was established and a preliminary compensating vent had been incorporated into the ground ephemeris. Based on this, the NC-2 solution decreased from 1.8 to 1.4 mps (6.0 to 4.6 fps). The Flight Dynamics team elected to delete this burn in order to save attitude maneuver propellant, making NC-3 the first and final opportunity to control phasing prior to day of rendezvous. After more tracking and refining of the vent value, the NC-3 burn solution stabilized to 1.0 mps (3.3 fps) posigrade ΔV. Ignition time was moved to the common node of the shuttle and ISS orbit planes so that NC-3 could be combined with NPC. The combined burn of 1.3 mps (4.4 fps) included 0.9 mps (3.0 fps) out-of-plane ΔV for planar control. As expected, the SMA trend continued after the post-NC-3 maneuver to the -XVV -ZLV overnight attitude (Figure 3). Since the compensating vent had been included in the NC-3 burn solution, proper orbiter-target range was achieved at the start of terminal rendezvous, in spite of ground drag model deficiencies.

The next morning, another noteworthy navigation issue arose during the "simo dump" that was performed prior to start of terminal rendezvous. Orbiter waste water and supply water are vented overboard simultaneously during the crew post-sleep period prior to every ISS rendezvous. Emptying the tanks helps to minimize the amount of dumping required during subsequent docked operations. Flight Rules govern the orbiter dump attitude in order to avoid particle re-contact with the orbiter or target (ref. 2). In the case of STS-110, as with most other ground-up rendezvous profiles, the dump orientation was starboard wing forward, payload bay-to-Earth (+YVV, -ZLV). This attitude was held from MET 1/11:45 to 1/14:20. During this period, the MCC Propulsion Officer reported frequent usage of the wake-firing reaction control thrusters (left pod yaw jets) to counteract the aerodynamic yaw torques on the vehicle, principally due to the orbiter's vertical tail being perpendicular to the airflow. Ground Nav personnel clearly observed the effects of the uncoupled jet firings in their processing of tracking data. A total SMA increase of 762 meters (2,500 ft) posigrade was detected at the end of the simo dump attitude hold just prior to the maneuver to NH burn attitude. About 183 meters (600 ft) of this can be attributed to drag modeling errors explained above, leaving the remainder due to the simo dump attitude hold. This is equivalent to more than 0.3 mps (1 fps) ΔV error. In addition to the propellant penalty, this large perturbation resulted in significant changes to burn targets just prior to the NH and NC-4 burns. For future shuttle rendezvous missions with large phase angles, a different dump attitude should be selected in order to assure symmetric vehicle attitude at low altitudes (e.g. tail forward with a roll bias). The expectation is that this will reduce jet firings, and therefore reduce perturbations. Mission planners for other spacecraft should also be aware of this—a symmetric vehicle orientation is desired when flying through high drag levels, especially during terminal rendezvous operations.

NH and NC-4 burns were targeted using preliminary simo dump tracking solutions. Sufficient tracking accuracy was obtained to allow the orbiter to hit the NC-4 point at 81 km (44 nmi) behind the target, vice 74 km (40 nmi) targeted. Both NH and NC-4 were large ΔV burns that brought the orbiter up to the ISS altitude of 393 x 380 km (212 x 205 nmi). The NCC burn, a Lambert-targeted 3 axis correction burn, was 0.8 mps (2.6 fps)—slightly larger than normal. Actual Ti position was 16 km (8.8 nmi) behind and 130 meters (425 ft) below the target (local vertical curvilinear coordinates), compared to planned 15 km (8.0 nmi) and 366 meters (1200 ft). Following a series of small midcourse correction burns, docking was successfully performed at MET 1/19:20. Table 3 summarizes the as-flown maneuver sequence for STS-110. From this table it can be seen that actual rendezvous propellant cost was 148 mps (485 fps). The pre-mission *planar-close* prediction, shown in Table 1, was 149 mps (489 fps). In order to examine the effect of drag error on total plan ΔV, the cost of those correction burns not predominately affected by drag must be removed. Stripping out NPC, NCC, and MC-1 through -3 from the actual sequence of events yields a total ΔV of 478 fps, compared to a pre-flight cost of 483 fps (here only NPC is removed since NCC and MC-1 through -3 are not budgeted pre-flight). Thus, for a 33% drag error, total rendezvous cost is affected by only 1%. This shows that, while drag modeling error can greatly alter individual burn solutions, overall propellant requirements are not significantly affected since most of the cost of rendezvous is driven by orbit height raising requirements.

Table 3. Trajectory Sequence of Events

Event	Flight Day	Planned TIG (MET)	Planned ΔV* (mps (fps))	Actual TIG (MET)	Actual ΔV (mps (fps))	Ha x Hp (km, (nmi))	Notes
OMS-2	1	0/00:39	29.7 (97.5)	0/00:38:45	29.3 (96.2)	230 x 157 (124 x 85)	
NC-1	1	0/03:35	4.9 (16.1)	---	---	230 x 157 (124 x 85)	Deleted in real-time
NC-2	2	0/16:51	2.4 (8.0)	---	---	228 x 156 (123 x 84)	Deleted in real-time
NPC	2	0/20:14	1.7 (5.5)	1/00:32:54	0.9 (3.0)	224 x 156 (121 x 84)	Combined w/NC-3
NC-3	2	1/00:14	0.9 (3.0)	1/00:32:54	ΔV_{TOT} =1.3 (4.4)	224 x 156 (121 x 84)	Combined NC-3/NPC
NH	2	1/14:50	59.4 (194.9)	1/14:43:53	66.5 (218.3)	391 x 213 (211 x 115)	
NC-4	3	1/15:34	44.9 (147.4)	1/15:27:30	44.8 (146.9)	391 x 369 (211 x 199)	Rng=81 km (44 nmi)
NCC	3	---	---	1/16:03:37	0.9 (2.8)	389 x 367 (210 x 198)	
Ti	3	1/17:06	2.7 (8.8)	1/17:01:19	3.2 (10.5)	391 x 380 (211 x 205)	Rng=16 km (8.8 nmi)
MC-1	3	---	---	1/17:21:19	0.1 (0.4)	391 x 380 (211 x 205)	
MC-2	3	---	---	---	---	391 x 380 (211 x 205)	
MC-3	3	---	---	1/18:09:49	0.9 (3.1)	391 x 380 (211 x 205)	
MC-4	3	1/18:23	0.9 (3.0)	1/18:19:49	0.8 (2.6)	393 x 380 (212 x 205)	

*Planned ΔVs for in-plane launch

CONCLUSIONS

Several noteworthy lessons were learned as a result of the high phase angle/low altitude rendezvous flown on STS-110. First, the MCC Jacchia-Lineberry atmosphere model over-predicted drag by 33% for a 230 x 157 km (124 x 85 nmi) orbit. The shuttle onboard computer model, Babb-Mueller, similarly over-predicted drag, but by a lesser amount. It is unclear whether errors were due to random atmospheric dispersions, or if indeed ground and onboard drag models systematically over-predict drag at low altitudes. Post-flight analysis of several widely used atmosphere models revealed that the extended U.S. Standard Atmosphere (COESA) would have provided the most accurate drag level during the low altitude portion of the mission. Additional flight data must be collected prior to confidently recommending an update to the MCC atmosphere model. Meanwhile, trajectory operations personnel should beware the possibility of large drag errors at low altitudes since this may significantly affect individual burn solutions. Overall rendezvous ΔV cost, however, showed little sensitivity to drag error, with the actual cost being only 1% different than predicted pre-flight, in spite of the 33% drag error. It is highly recommended that a quiet tracking arc of at least six hours be performed as soon as possible after launch for any future low altitude mission in order to determine actual drag levels and calibrate propagators. Eventual use of MCC filtered state vectors from the shuttle GPS receiver may provide more rapid determination of perturbations and drag modeling errors (ref. 10). Another recommendation is to avoid asymmetrical vehicle attitudes at low altitude that generate large aero-torques and associated uncoupled reaction control system jet firings. This should be avoided particularly during the final phase of rendezvous when highly accurate burn solutions are required. Rather, symmetric attitudes are desired in order to minimize jet activity and associated perturbations.

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